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An optimization model for the combined planning and harvesting of sugarcane with maturity considerations

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Planting and harvesting are important stages in the sugarcane crop cycle, because well planned planting and harvesting phases promote a series of benefits throughout the cultivation cycle and in the subsequent industrial use of the products. These benefits are operational, economic and environmental such as: improved utilization of the land area and transport logistics; an increase in sugarcane output; better cane reception in the factory; in administrative simplification of the industrial activities; in enhanced response to the demands of the industry; in cost planning; and in the control of pests and weeds. In this work a methodology of optimal cultivation planning to sugarcane planting and harvesting is proposed. The cultivation plan is for 5 years; and key decisions to be made in this period are to determine the planting date, the variety selection and the harvesting date corresponding for each plot such that the global production is optimized. We propose a mathematical model for this optimization task. The model uses computational and mathematical strategies to ensure that date of harvesting is always in period of the maximum maturation of the sugarcane and considers all demand and other operational constraints of the processing mill. The binary nonlinear optimization model was solved by a proposed genetic algorithm, giving an optimum plan with a potential sugarcane production 17.8% above production obtained by conventional means in the mill.

Key words: Genetic algorithm, integer nonlinear optimization model, optimal planning, *Saccharum* spp., sugarcane planting and harvesting.

INTRODUCTION

The growing of sugarcane has been gaining importance in recent years in several countries of the world due its use in the production of sugar, ethanol alcohol and electrical power from its bagasse and residue of

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harvesting. Due to expansion of this crop in recent years, an efficient sugarcane production planning system for new and renewed areas becomes essential, because it will help produce optimal economical, social and environmental benefits of the sugar-alcohol sector. According to Scarpari and Beauclair (2010), optimized agricola planning is a fundamental activity for increasing the quantity and quality of the sugarcane crop. This in turn enhances the sugar-alcohol industrial sector as it increase profits and decrease costs. In this context the need for a decision support technique that helps the mill manager to obtain an optimized planning system for sugarcane production is evident. Due to the complexities involved, this system necessarily needs to contain one or more mathematical optimization tools. The literature contains some works focused in planning the cultivation of sugarcane using optimization techniques with the objective of improving the quality and quantity of the raw material in sugar-alcohol mill. These are reviewed below.

Piewthongngam et al. (2009) propose an optimization model for planning and cultivating sugarcane. The model aims to select the period and variety for planting in order to avoid oversupply during the peak harvest time. The plan ensures that the cane is cut properly throughout the harvest period, hence optimizing the global sugar production.

Jena and Poggi (2013) propose a planning system specifically for sugarcane harvesting aiming to improve the production of sugar and ethanol in a specific mill in Brazil. The authors present an optimization model for tactical and operational planning such that the total sugar content in the harvested sugarcane is maximized. They present a case study to illustrate the benefits of the proposed planning. These authors consider the total profit increase of 2.6% as satisfactory, but discuss the difficulties encountered regarding computational time and the need for studies that develop new techniques for this problem.

There are many other works addressed using optimization techniques to improve processes for cultivation and exploitation of sugarcane. But these studies do not necessarily consider the planning for sugarcane planting and harvest over a medium term planning period, nor incorporate the maturity date of the sugarcane into their models. They hence may obtain results with a low exploitation of the quality of the sugarcane, (Buddadee et al., 2008; Florentino et al., 2015; Florentino and Pato, 2014; Higgins et al., 1998; Leboreiro and Hilaly, 2011; Salassi et al., 2002; Stray et al., 2012). In this work, we propose a methodology to optimize the cultivation planning for sugarcane planting and harvesting.

The cultivation plan is for a five years period and determines the planting date, the variety selection and the harvesting date corresponding for each plot such that the global production is optimized. The methodology uses computational and mathematical strategies to ensure that date of harvesting is always in the period of the maximum maturation of the sugarcane.

MATERIALS AND METHODS

This work proposes a methodology that aims to produce an optimal planting and harvesting plan for the sugarcane crop. Therefore, we present here a mathematical model as a tool for determining this plan. A Genetic Algorithm is developed to solve the resulting mathematical model.

We propose an integer nonlinear optimization model to assist in the planning of sugarcane planting and harvesting during a 5 years (4 cuts) planning period such that the overall sugarcane production is optimized. This integer nonlinear optimization model is difficult to solve with commercial software due to the relatively large number of binary variables and hence a heuristic approach is required. Therefore, we propose a genetic algorithm (GA_PlanHarv) that has a relatively straightforward computational implementation and interpretation of results.

A mathematical model is proposed to choose the sugarcane variety i to be planted in each available plot j, to determine the appropriate period t_o for this planting and to determine the period t_c for harvest in the four years following the year of planting; in order to maximize the total sugarcane production over five years, i.e. four cuts (c=1,2,3,4). Where i=1,…n; j=1,…k; $t_o=t_{o1},…t_{oz}$; $t_c=t_{c1},…t_{cs}$; c=1,2,3,4; n is the number of the varieties adaptable to local climate and soil; k is total number of the plots available for sugarcane planting; z and s are the numbers of months appropriate for the planting and harvesting of sugarcane respectively.

According to Rudorff et al. (2010), the sugarcane cycle is semi-perennial and begins with the planting of a stem cutting that grows for about 12 months (called *year sugarcane*) or 18 months (called *year-and-half sugarcane*). The main climate components which control growth, production and quality of the sugarcane are temperature, light and moisture availability, so the most appropriate months for sugarcane planting in Brazil are January, February and March for *year-and-half sugarcane*; September and October for *year sugarcane*; in this way the climate assists the correct development of this culture. The sugarcane cut should be made from April to December, because these are the optimal months for harvesting in Brazil due humidity and temperature. After the first harvest, the ratoons are harvested annually for a period of about 5 years. Successive harvests lead to a gradual yield loss until the crop is no longer economically profitable. At this point, the cycle is interrupted, and the area is renovated with the planting of the new stem cuttings. Should the ripe sugarcane not be harvested, it will keep on growing, but loses a lot of its sucrose and fibre quality. An important sugarcane quality parameter for assessing cane maturity is the sucrose percentage or also referred to as pol percent (pol% cane). Pol% cane is the sucrose percentage present in sugarcane juice.

In the formulation of the mathematical model two possible periods for planting are considered. The first is P1={January, February, March} for *year-and-half sugarcane* and the second is P2={September, October} for *year sugarcane* or referring the month by number: P1={1,2,3} and P2={9,10}. Thus, if the sugarcane is planted in period P1 the first harvest is made 12 months after planting, and if the sugarcane is planted in period P2 the first harvest is made 18 months after. From the second harvest onwards, the cut is always made approximately after each 12-month period. It is very difficult to obey exactly the mentioned periods for harvesting the sugarcane due to the technical capabilities of the mill (machinery, milling, transportation, etc.). Therefore, harvest up to two months before or after these time points is permitted.

Figure 1 illustrates a planning for 5 years (60 months) of a *year-*
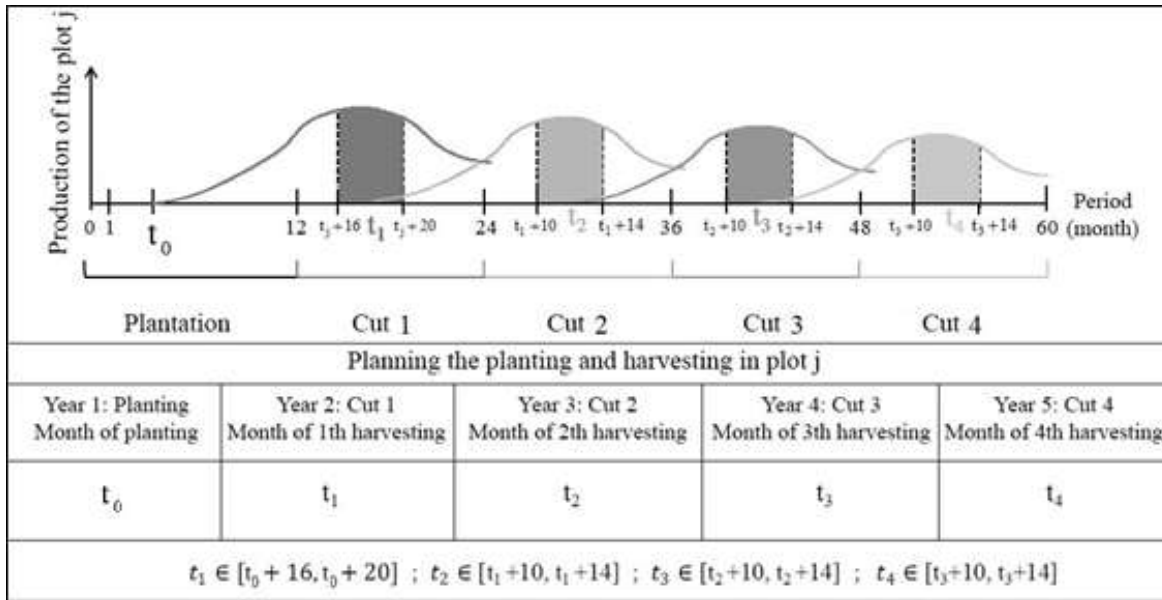
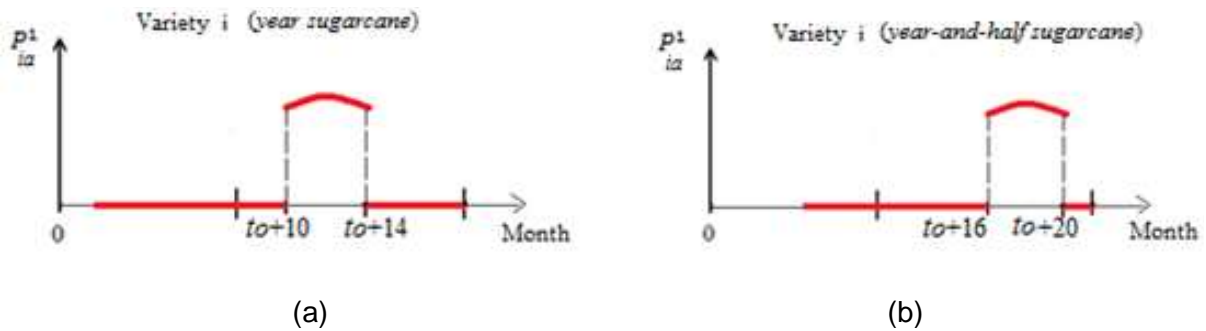**Figure 1.** Planning the planting and harvesting in plot j.

(a)   (b)

Figure 2. Function P_{ia}^1 for the cases of the first cut of *year sugarcane* and *year-and-half sugarcane*.

and-half sugarcane of variety *i* planted in plot *j*. In the first year of this planning the sugarcane should be planted in month $t_o \in$ P1. The first cut should be done preferably 18 months after planting, and may vary within a two month interval, ie, the first cut should be conducted in month $t_1 \in [t_o + 16, t_o + 20]$. The second cut should be done in month t_2 preferably 12 months after t_1, belonging to the time interval $[t_1 + 12, t_1 + 14]$, and so on. Thus, during the five year planning horizon, the sugarcane will always be harvested within its high productivity interval.

The optimal time for first cut depends if the sugarcane is *year sugarcane* (12 months) or *year-and-half sugarcane* (18 months) and for the next cuts is 12 months for both. The sugarcane productivity (P_{cia}), pol %cane (A_{ica}) and fibre (F_{ica}) vary with cut number (*c*), sugarcane variety (*i*) and period of time that it remains in field (*a*), then is advisable that harvesting in all plots is undertaken very close to the optimal time (Colin, 2009, Rudorff *et al.* (2010)). To force a plan with a cut of the sugarcane close to the optimal time the following productivity function is proposed.

Let *i* be a index associated with sugarcane variety and P_{ia}^1 the produtivity of the variety *i* when it is harvested *a* months after the planting or most recent cut. This produtivity function is defined as follows.

$$P^C_{ia} = \begin{cases} P_{cia} \ge 0, \text{if } a \in [t^o, t^{oo}] \\ 0 \quad \text{otherwise} \end{cases}$$

Where:

P_{cia} is the known productivity of the sugarcane of variety *i*, in the *c-th* cut and it has *a* months that were planted or cut ($0 < a \le 18$; *i*=1, 2, …, *n*; *c*=1,2,3,4; n is the total number of the sugarcane varieties adaptable to local climate and soil);
$[t^o, t^{oo}]$ =[10, 14] if (*c*=1 and *i* is *year sugarcane*) or if (*c*>1);
$[t^o, t^{oo}]$ =[16, 20] if (*c*=1 and *i* is *year-and-half sugarcane);*

The graphical representation of the function P_{ia}^1 for the cases of the first cut of *year sugarcane* and *year-and-half sugarcane* are shown in Figure 2.

Let x_{ijt} and y_{jt} be decision variables, such that: x_{ijt}=1 if variety *i* is planted in plot *j* at time *t* and x_{ijt}=0 in the contrary case, y_{jt}=1 if the sugarcane variety planted in plot *j* is harvested in time *t* and y_{jt}=0 in the contrary case. The proposed model is therefore:

$$max\left(\sum_{j=1}^{k}\sum_{i=1}^{n}\sum_{t_o\in\{P1\ or\ P2\}}\left(\sum_{t_1=t_o+10}^{t_o+20}\left(P1_{i(t_1-t_o)}x_{ijt_o}y_{jt_1}+\sum_{t_2=t_1+10}^{t_1+14}\left(P2_{i(t_2-t_1)}y_{jt_2}L_j+\sum_{t_3=t_2+10}^{t_2+14}\left(P3_{i(t_3-t_2)}y_{jt_3}L_j+\sum_{t_4=t_3+10}^{t_3+14}P4_{i(t_4-t_3)}y_{jt_4}L_j\right)\right)\right)\right)\right)$$

(1)

Subject to:

$$\sum_{i=1}^{n}\sum_{t_o\in\{P1\ or\ P2\}}x_{ijt_o}=1\qquad j=1,\dots,k$$

(2)

$$\bar{i}_j=\sum_{i=1}^{n}\sum_{t_o\in\{P1\ or\ P2\}}x_{ijt_o}\,i\qquad j=1,\dots,k$$

(2a)

$$t_{o\,j}=\sum_{t_o\in\{P1\ or\ P2\}}x_{\bar{i}_jt_o}\,t_o\qquad j=1,\dots,k$$

(2b)

$$\sum_{t=t_o+10}^{t_o+20}y_{jt}=1\qquad j=1,\dots,k$$

(3)

$$t_{1j}=\sum_{t=t_o+10}^{t_o+20}y_{jt}\,t\qquad j=1,\dots,k$$

(3a)

$$\sum_{t=t_c+10}^{t_c+14}y_{jt}=1\qquad j=1,\dots,k\qquad c=1,2,3$$

(4)

$$t_{(c+1)j}=\sum_{t=t_{cj}+10}^{t_{cj}+14}y_{jt}\,t\qquad j=1,\dots,k\qquad c=1,2,3$$

(4a)

$$\sum_{j=1}^{k}A_{\bar{i}_jc(t_{cj}-t_{(c-1)j})}y_{jt_{cj}}\geq D_c\qquad c=1,2,3,4$$

(5)

$$FI\leq\sum_{j=1}^{k}F_{\bar{i}_jc(t_{cj}-t_{(c-1)j})}y_{jt_{cj}}\leq FS\qquad c=1,2,3,4$$

(6)

$$\sum_{t=1}^{t_j}\sum_{j=1}^{k}L_jx_{ijt}\leq 0.15\qquad i=1,\dots,n$$

(7)

$$MI\leq\sum_{j=1}^{k}L_j\,P^c{}_{\bar{i}_j(t_{cj}-t_{(c-1)j})}y_{jt_{cj}}\leq MS\qquad c=1,2,3,4$$

(8)

$$x_{ijt}=0\ or\ 1\quad i=1,\dots,n\ ;\ \ j=1,\dots,k;\quad t=1,\dots,60$$

(9)

$$y_{jt}=0\ or\ 1\qquad j=1,\dots,k\ ;\qquad t=1,\dots,60$$

(10)

Where:
n is the number of the sugarcane varieties adaptable to the local climate and soil; k is the number of the plots available for planting; i

$= 1, 2, ..., n$ is the index associated to sugarcane variety; $j = 1, 2, ..., k$ is the index associated with the plots; $t = 1, 2, ..., 60$ is the index associated to time in month for planning; L_j is the area of the plot j in ha; $P^C{}_{ia}$ is the productivity of the variety i when it is harvested a months after planting ($a=t_c-t_{c-1}$); A_{ica} is the productivity of the pol %cane of the sugarcane variety i in t.ha^{-1} when it is harvested a months after the last cut ($a=t_c-t_{c-1}$); D_c is the demand of sugar (in tons) in the year of the cut c; F_{ica} is the productivity of the fibre of the sugarcane variety i in t.ha^{-1} when it is harvested a months after the most recent cut ($a=t_c-t_{c-1}$); FI and FS are the lower and upper bounds for the sugarcane fibre at any time. The mills in the São Paulo state of Brazil use $FI = 8\%$ and $FS = 14\%$; MI and MS are the lower and upper bounds for the sugarcane milling capacity of the mill.

The model determines which month t_o and which sugarcane variety i will be planted in each plot j in first year of the planning and during which period t this sugarcane will be harvested in next 4 years of planning, so as to maximize the objective function (1) related with sugarcane production during this 5 year (4 cuts) period. The constraints (2) guarantee that there will be sugarcane planting in all plots j in the first year of the planning, in months belonging to P1 or P2. The Equation (2a) derives $\bar{i}_j$ (the index of the sugarcane variety to be planted in plot j) and the equation (2b) derives t_{oj} (the month that the sugarcane variety $\bar{i}_j$ must be planted in plot j). The constraint set (3) guarantees that there will be sugarcane harvesting in all plots j in the first year of planning. The equations (3a) calculate t_{1j} (the month that will be the first sugarcane harvesting in plot j). The constraint set (4) guarantees that will be sugarcane harvesting in all plots in years 2, 3, 4 of the planning. The equations (4a) derive t$_{cj}$, $c=2,3,4$ (the month that will be sugarcane harvesting in all plots j in years 2, 3, 4 of the plan). The constraint set (5) guarantees the production of the pol %cane demanded by the mill in the planning period. The constraint set (6) guarantees the production of the fibre demanded by the mill in planning period. The constraint set (7) guarantees that each sugarcane variety will be planted in a maximum of 15% of the total area intended for planting. This is a requirement of the Brazilian mills to prevent pests and diseases. The constraint set (8) guarantees that the capacity of the mill for sugarcane grinding will be satisfied in all harvest periods and the constraints (9) and (10) define the decision variables of the problem as binary.

The model (1)-(10) is a binary nonlinear program (INLPP 0-1) which is difficult to solve, especially when it has large numbers of plots and varieties. The number of plots in current mills can make it impossible the solve using classical optimization techniques; this paper therefore investigates heuristics for determining good quality feasible solutions. A Genetic Algorithm is proposed, as follows.

Genetic Algorithm: GA_PlanHarv

The genetic algorithm (GA) was developed by Holland (1975). GA is based upon evolutionary Darwinian principles. An individual that has good fitness in a population has a greater chance of passing its genes to future generations via reproduction or crossover. Species carrying the correct combinations in their genes become dominant in their populations. Sometimes, occur mutations in genes and arise new species. Unsuccessful changes are eliminated by natural selection.

In this technique, a solution is called an *individual* or *chromosome*. A collection of individuals is called a *population*. The
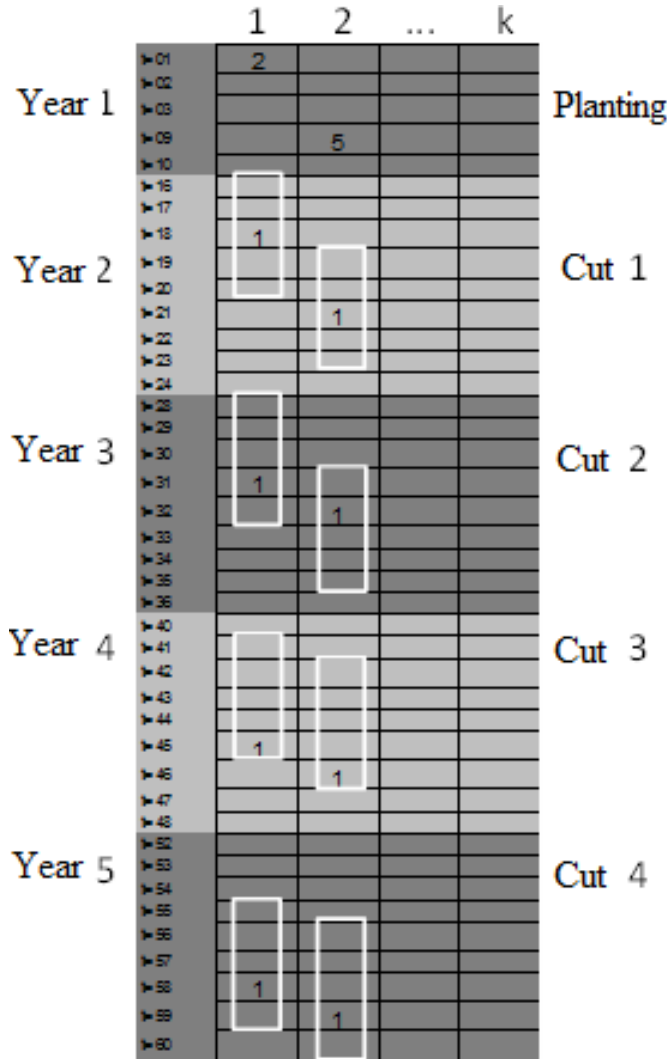
Figure 3. Chromosome structure.

Figure 4. Crossover process.

individual is a plan for planting and harvesting of the farm, and it is composed of the a matrix with k columns representing the plots and 41 rows representing the 5 months of planting belonging to P1 and P2, and 36 months for harvesting for the four cuts (9 possible months for harvest in each year). For the creation of these individuals, firstly two random numbers are chosen for each column of the matrix: an integer number in the interval [1, n] and another integer number in the interval [1, 5]. The first number represents the sugarcane variety to be planted in each plots j (column j), chosen among the sugarcane varieties (listed from 1 to n), and the second number represents the period when this variety will be planted in each plot j. After planning the planting we beginning the harvest planning. For harvest planning, a month is chosen randomly in all years intended for cutting of the sugarcane for each plot, but such that the constraints (3), (4) and (10) are satisfied. This structure of the individual satisfies the constraints (2), (3), (4), (9) and (10), is shown by Figure 3.

The evaluation of the individuals is made by their *fitness* value. The *fitness* for each individual is measured as follows:

$$f_{ind} = FO_{ind} - p_{ind}.$$

Where f_{ind}, FO_{ind} and p_{ind}, are respectively the *fitness*, the objective function value and the penalty of the individual ind. The penalty p_{ind} of individual ind is zero if the individual is related to a feasible solution to the mathematical model and $p_{ind} = 0.8\,FO_{ind}$ for an infeasible solution.

In the first iteration a copy of the best individual (with highest fitness) is made and this is updated in later iterations if a superior individual is found. After all individuals are evaluated, the genetic operators are applied.

The first genetic operator to be applied is the *selection*. In all iterations of the population Pc% individuals are copied into an *intermediate population* to perform *crossover*. In this work the selection of individuals to be copied is made via Roulette Method (Holland, 1992). This method was chosen because empirical tests showed that this approach was more efficient than others. The second genetic operator is the *crossover*. In this process is chosen randomly two individuals among the elements of the *intermediate population* (copied by selection), called *Parent 1* and *Parent 2*, and a cutting place from the columns of the matrices representing those individuals is chosen by sampling a uniform random discrete variable. This process assists the separation of the genes that form two new individuals (*child 1* and *child 2*) while keeping characteristics of the parents, as shown in Figure 4.

The mutation is the third genetic operator. After crossover, individuals from the current generation are randomly selected for the mutation. A draw with low probability ($pm < 0.05$) is realized for each individual, in order to determine whether to change the information contained in these genes. If the number drawn is less

initial population can be randomly started or built. GA uses the operators *selection*, *crossover* and *mutation* to generate new solutions from existing one. In crossover, two solutions are generally combined to form a new individual. The solutions are *selected* among existing solutions in the population using some methods for the selection (e.g. Roulette Wheel Selection, Boltzman Selection, Tournament Selection, Rank Selection and Steady State Selection). These methods in general give a preference for individual with better *fitness*, so that a new individual is expected to inherit good characteristics. By iteratively applying the crossover operator, characteristics from good individuals are expected to appear more frequently in the population, eventually leading to convergence to an overall good solution. The mutation operator introduces random changes in the characteristics of individuals, generally applied at the discrete unit of solution level with the probability of changing the properties of a unit being very small– typically less than 1%.

The individuals in the proposed GA in this work (GA_PlanHarv) are generated using a random/constructive heuristic in order to comply with the periods of planting (P1 and P2) and cuts such that the genetic operators preserve this feasible structure. Each
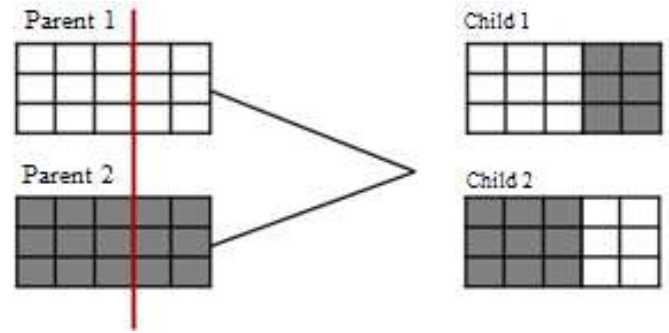
Table 1. Average data of the varieties in the first year of the cultivation.

Variety	Productivity (t ha⁻¹)	Pol (%)	Fibre (%)	Harvest season
CTC 15	132.80	14.50	12.36	July - December
CTC 9	100.00	15.84	12.34	April - July
RB925211	89.29	14.67	12.30	May - August
CTC 6	136.00	14.98	11.16	August - December
RB855156	117.80	14.50	12.41	April - May
CTC 2	129.10	14.31	12.21	June - October
RB857515	148.20	14.82	11.47	July - December
SP80-1842	112.80	14.90	12.90	June - October
SP83-2847	126.70	13.20	12.74	July - December
SP80-3280	121.70	14.80	11.30	July - December
RB928062	113.00	15.75	12.38	September - December
RB966928	123.10	13.32	11.97	April - July
CTC 20	165.00	13.50	11.50	May - December
CTC 17	112.30	14.98	12.38	April - August
SP81-3250	140.60	15.02	12.91	June - October
CTC 4	130.90	13.54	11.80	June - November
RB92579	142.40	15.70	12.93	July - October
RB855453	133.35	13.90	12.38	April - July

Sources: CTC (2012) and RIDESA (2008).

Table 2. Parameters used for the implementation of the GA_PlanHarv.

G	N	Pc	Pm	n	MI	MS	D	FI	FS
3500	200	0.8	0.05	18	850	3200	114	8%	14%

Where: G is the maximum number of generations; N is the number of individuals in population; Pc is the crossover rate; Pm is the mutation rate; n is the number of sugarcane varieties adaptable to local climate and soil; MI and MS are the lower and upper bounds for the sugarcane milling capacity of the mill (tons month⁻¹); D is the demand for sugar (in tons month⁻¹); FI and FS are the lower and upper bounds for the sugarcane fibre.

than pm the change will occur, otherwise it will not occur.

In order to choose the gene to undergo change, as well as the new value to insert in this gene another draw takes place. These individuals are then evaluated (computing their *fitness* values). The NP best individuals from the previous population and the new individuals produced form the new population. The entire process is repeated until a pre-specified stopping criterion is achieved. This paper chooses the number of generations as the stopping criterion. The solution that offers the best fitness in the final generation is considered as the recommended solution to the problem.

RESULTS AND DISCUSSION

We validated the proposed methodology on a real case of a Brazilian farm in São Paulo state with the area of agricultural holdings of 183.12 hectares, divided into 21 plots for planting of the sugarcane, which are labeled from 1 to 21. The planning of the culture was conducted by a team composed of members of the agricultural and technical departments and coordinated by an agronomist. The planning was conducted during the period from July to September of the year before planting. The plan was executed and obtained a production total of 61,909.69 tons in four cuts.

For the planning of planting and harvesting of the sugarcane during a 5 years (4 cuts) period using the model (1)-(10), such that overall sugarcane production is optimized we use 18 candidate varieties for planting, which are presented in Table 1. Here we use the parameters presented in Table 2 to solve the model (1)-(10) using the GA_PlanHarv.

The GA_PlanHarv was implemented with MATLAB 7.6.0.324 (R2008a) software MATLAB (Matrix Laboratory, version 2012), and run on a micro-computer Dual Core i5-650 with 4 GB memory and a 400 GB hard drive, for a planning period of 5 years of the planting and harvesting of sugarcane in the cited farm and the results are presented in Table 3. The results can be achieved in an average of 50 min, an acceptable timeframe given the strategic nature of the planning process.

The agronomists typically spend about three months

Table 3. Planning of sugarcane planting.

Variety to be planted	Plot (J)	Area of plot (ha)	Total area (ha)	Month of planting
CTC 15	7	10.06	10.06	m_3
RB925211	4	4.68	4.68	m_2
CTC 6	8, 14	10, 7.39	17.39	m_1, m_2
RB857515	6, 10, 19	4.74, 10, 9.83	24.57	m_1, m_2, m_3
SP80-1842	13	8.1	8.1	m_2
RB966928	1, 9, 12	7.86, 8.19, 6.09	22.14	m_3, m_1, m_1
CTC 20	18, 20	10.03, 16.39	26.42	m_{10}, m_{10}
CTC 17	3	15.81	15.81	m_1
SP81-3250	5, 11, 15, 17	5.45, 8.14, 8.47, 4.75	26.81	m_1, m_3, m_2, m_1
RB855453	2, 16, 21	11.81, 8.31, 7.02	27.14	m_1, m_3, m_3

m_1= January, m_2= February, m_3= March, m_{10}= October

Table 4. Planning of the 4 cuts of the sugarcane harvesting.

Plot	Harvest season
1	m_7, m_6, m_6, m_7
2	m_5, m_6, m_4, m_4
3	m_4, m_5, m_5, m_6
4	m_5, m_7, m_7, m_5
5	m_8, m_8, m_8, m_8
6	m_7, m_9, m_{10}, m_{10}
7	$m_{10}, m_{10}, m_{10}, m_{10}$
8	m_9, m_9, m_{11}, m_{11}
9	m_4, m_4, m_6, m_5
10	$m_{10}, m_{11}, m_{12}, m_{11}$
11	$m_9, m_{10}, m_{10}, m_{10}$
12	m_4, m_5, m_5, m_7
13	m_8, m_9, m_9, m_{10}
14	m_8, m_8, m_{10}, m_9
15	m_6, m_8, m_7, m_8
16	m_6, m_5, m_4, m_5
17	m_6, m_6, m_7, m_9
18	$m_{11}, m_{12}, m_{11}, m_{12}$
19	m_7, m_7, m_8, m_7
20	m_{12}, m_{11}, m_9, m_9
21	m_5, m_7, m_7, m_7

m_4=April m_5=May m_6=June m_7=July m_8=August m_9=September m_{10}=October m_{11}=November m_{12}=December

planning this culture, thus a mathematical and computational tool like GA_PlanHarv can be an important and quick assistance for to assist them in achieving optimized decision making.

Table 3 shows that was possible to determine the planting plan using 18 sugarcane candidate varieties. The model chooses 10 among these 18 sugarcane varieties for planting. We note that the RB855453 variety has the greatest area of 4.68 ha. Regarding the months of planting we observe that the months intended for planting are well distributed.

The proposed model was able to plan the planting of sugarcane during the correct period, using all the available area and achieved a good distribution of the varieties.

Table 4 presents the results of the sugarcane harvesting planning during the 5 years of the cultivation of the sugarcane (4 cuts).

Table 4 shows that the model was able to plan the harvest for the proposed five years (four cuts) and satisfied all demands and technical capabilities imposed by mill.

The model plans the planting and harvesting together in an optimized manner, considering the mill conditions. In this way, it becomes easier to achieve goals, attend to the required demand and meet the constraints imposed by the mill.

Figure 5 shows the increase of the sugarcane production values during the computational development of the generations in the proposed GA for planning of the sugarcane planting and harvesting and compares these values with the actual value of the production presented by mill manager.

The Figure 5 shows that in 30 iterations of the proposed GA, the value of production estimated by the proposed model exceeded the value of the production given by mill manager. The estimated value for sugarcane production found by model was 75,319.61 tons for the five years of the planning, which corresponds to 13,409.92 tons more than the value presented by mill manager, representing an increase of 17.8% in sugarcane production.

The proposed methodology for the optimized planning of the process of planting and harvesting of sugarcane has a strong potential to assist mill managers, supporting decisions in a quick and safe way.

Conclusion

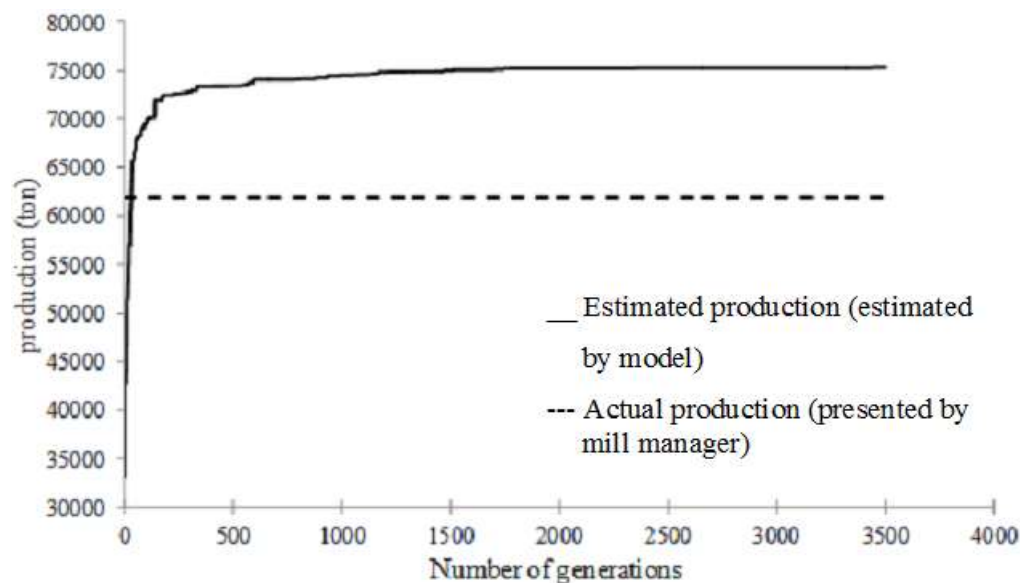This paper has developed a binary nonlinear optimization

Figure 5. Sugarcane production, in tons, depending on the number of generations for the farm area.

model for decision support in the planning of planting and harvesting of the sugarcane for a period of five years, such that overall sugarcane production is optimized. The model uses mathematical strategies to enforce that the date of harvesting is always in the period of the maximum maturation of the sugarcane and considers all demand and other operational constraints of the mill. A genetic algorithm (GA_PlanHarv) is developed for efficiently solving the full binary nonlinear optimization model, finding good quality feasible solutions that meet the needs of the manager for the complex decisions involved.

The proposed methodology proved to be a good tool for the optimized planning of the planting and harvesting of the sugarcane, increasing by 17.8% the production as compared with that presented by the mill.

Due to the global energy and climate change crisis, sugarcane has become one of the most important crops in tropical and subtropical countries due to its use in bioenergy production, and additionally because the sugarcane can be used in sugar production. It is therefore an important product for the economy of those countries. However, this crop has undergone a recent and rapid expansion, resulting in the need for tools that assist managers of the mills in their decision making and implementation of their planning. Thereby it can be concluded that this research offers a worthwhile contribution by providing an effective mathematical tool with an efficient computational implementation that can offer results potentially better than those traditionally obtained in mills in a reasonable computational time.

Conflict of interests

The authors have not declared any conflict of interests.

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